**Item title:** Design of a multi-agent, fiber composite digital fabrication system

# Design of a Multi-agent, Fiber Composite Fabrication System

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**Abstract**
Designing novel platforms that can use new materials and fabrication strategies in a fully autonomous, cooperative fashion can help create architectures faster and more reliably in remote environments.

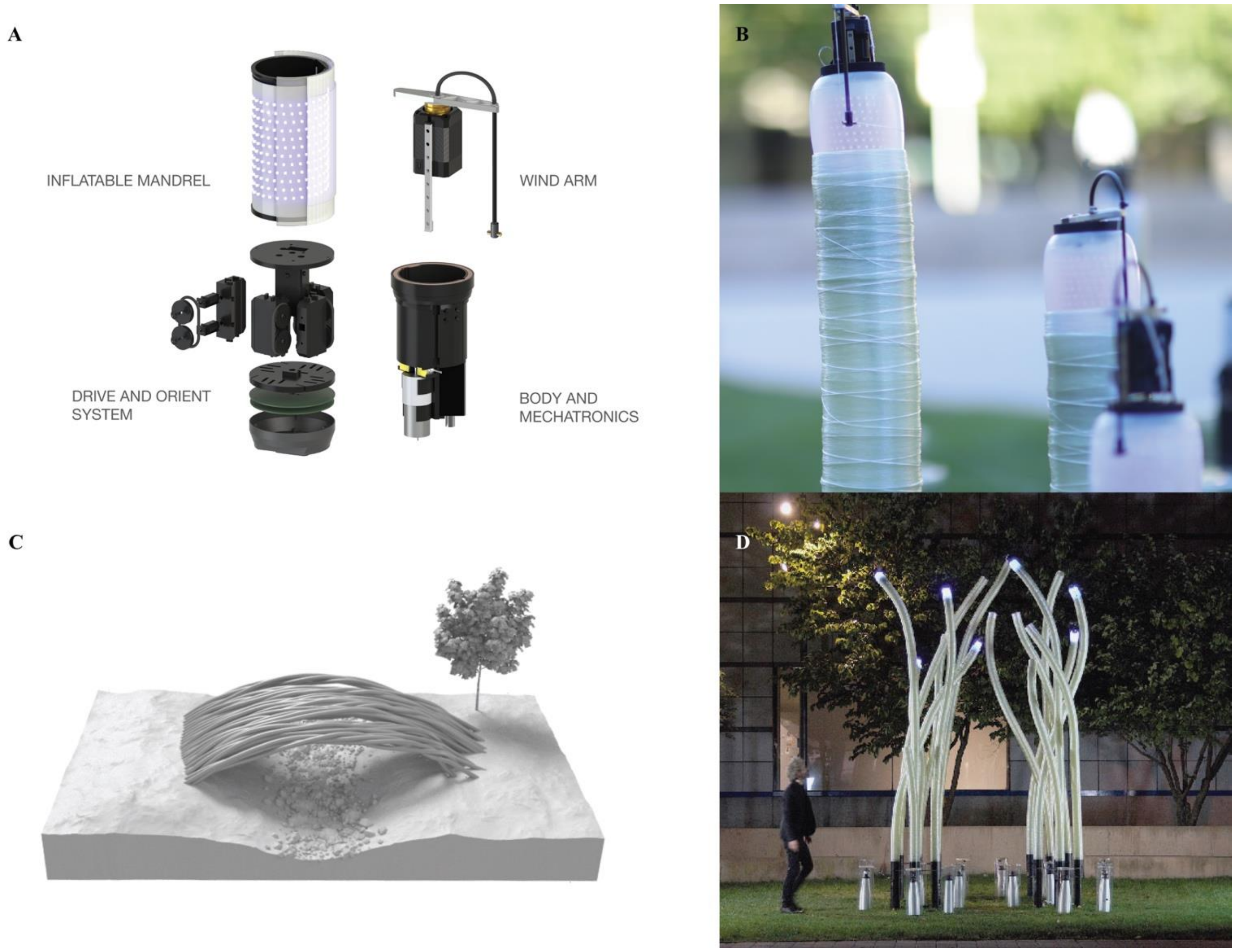


**Fig. 1. (A**) Each Fiberbot consists of a wind arm, a reversibly inflatable mandrel, and subsystems for navigation and control. (**B**) By winding fiber and photocurable resin around themselves, robots create fiber-reinforced composite tubes that they can climb and extend. (**C**) A possible application of the system to create a useful structure is proposed using a design flocking framework, although the spacing between tubes is narrower than can be fabricated by our current system. (**D**) An architectural scale print was built by 16 identical Fiberbots operating in parallel over two days.

Some of nature's most successful organisms are builders. Spiders can vary chemical compositions of their silk to create complex webs that are lightweight yet highly durable to trap prey. Ants, bees, and termites rely on simple communication strategies to coordinate and parallelize construction tasks. These species crawl on their own structures to expand their work volume. Humans are similarly interested in more efficient construction materials and strategies to automate, parallelize, and scale construction. Inspired by nature, we aimed to combine fibrous composite materials with a multi-robot fabrication system to efficiently create on-site architectural structures that withstand variable environments.

Previous studies identified autonomous mobility and simple communication as key components of scalable, cooperative multi-robot construction, but mainly focused on assembly of pre-fabricated parts [1], [2]. Nature ubiquitously relies on fibers and hierarchical fiber arrangements, such as those found in trees or bones, for strength and flexibility [3], [4]. Recent work [5], [6] suggested synthetic fiber-reinforced composites (FRC), such as fiberglass or carbon fiber, can mimic aspects of natural materials to achieve more complex and higher-performing properties in architecture. However, the molds –or *mandrels*–required to create these architectures are geometrically constrained and expensive to make and maintain. A process that allows fabrication of more complex geometries without sophisticated infrastructure is important to automating FRC construction at scale and on-site.

To explore these possibilities, we present a novel autonomous fabrication system that combines FRC and hierarchical design methodologies with a parallelized fabrication strategy. A team of Fiberbots, each an identical robot consisting of a fiber winding system that uses fiberglass thread and UV-curing resin, builds self-supporting composite tubes. Each robot is mobile, allowing it to create a single tube of pre-specified curvature, up to tens of times longer than itself. Individual tubes are interwoven and constructed simultaneously by multiple robots working in parallel, to create larger architectural structures.

*Creating fiberglass tubes with controlled curvature and arbitrary length*

Initially, an autonomous system is needed that can create large, specified fiberglass structures. Each robot constructs an independent tube sequentially, one segment at a time from a single strand of fiberglass thread and photocurable resin. Each segment, up to 90 mm in length and roughly 100 mm in diameter, is appended with overlap to the end of an existing tube, and then cured and bonded to the growing structure. Controlled curvature is achieved in the tube by tilting each segment relative to a previous segment.

Each robot embodies a mandrel with an inflatable silicone membrane that fixes the robot to the existing structure and provides a cylindrical mold. A wind arm pulls fiber and resin from a ground-based storage system, mixes the materials in the nozzle and deposits the composite mixture onto the surface of the mandrel. The wind arm also controls segmental fiber patterning and thickness. Through mandrel inflation or deflation, various diameter tubes are created. By sufficiently shrinking its radius, through deflation, the mandrel can detach from the cured structure, allowing the robot to drive along the length of the tube. The fabrication sequence of each segment is thus (1) *inflate* the mandrel to the segment diameter required to anchor the robot to the existing tube, (2) *wind* the composite, (3) *cure* the composite, (4) *deflate* the mandrel to free the robot from the structure, (5) *drive* the robot upwards, and (6) *orient* the robot to start the next segment (fig. S1).

The robot has four treads that allow it to crawl along its tube, including horizontal and inverted tube orientations. An on-board IMU and tread-mounted encoders help the robot localize along its tube, enabling odometry-based control. Each robot is controlled via a custom programmatic software interface, similar to G code used in 3D printers. This interface allows designers to specify motion commands or request state information about the robot, and provides a flexible means of interacting with the system to fabricate a wide range of segment patterns and tube geometries.

*Scaling to multiple robots and full architectures*

A single Fiberbot can construct an individual tube with specified curvature and length. Because the tubes are self-supporting, it is possible to create useful architectural surfaces and volumes, such as walls or bridges, by building side-by-side or interwoven tubes. Interwoven tubes can act as co-supporting structures to handle additional load. These architectures can be fabricated in parallel with a large team of robots, however, collision avoidance and fabrication constraints limit design complexity and fabrication time. We used a custom algorithm, adapted from Reynold's flocking behaviors [7], to design structures in addition to generating collision-free trajectories for the robots, quickly and all in a single step.

To demonstrate the capabilities of the multi-agent fabrication system, we developed 16 identical robots that autonomously created a real-world structure at architectural scale. The robots were successfully used in parallel, with no collisions, to fabricate a pre-designed structure over a two day period. They were designed and manufactured in-house by the authors, using primarily off-the-shelf components and 3D printed parts. The robots fabricated curved tubes ranging in length from 2.5 m to 4.1 m with overhangs that reached 1.5 m horizontally. The resulting structure, including its re-usable scaffold base, was roughly 4.5 m tall, took 12 hours to set up and fabricate, and remained on-site for seven months spanning fall and winter in Cambridge, Massachusetts. It resisted damage from weather, including rain, strong winds, and heavy snow (fig. S2).

*Future opportunities and challenges*

The Fiberbots system demonstrates the feasibility of autonomous, cooperative, continuous construction, and exploring new building materials, such as FRCs. Though additional implementation of sensors for localization, manipulation and controls is needed to fully realize the system, we have demonstrated a novel fabrication method, introducing new ways to both digitally design and fabricate on-site. This approach to simultaneously designing end-to-end fabrication platforms, material systems, and algorithms can increase manufacturing capacity, enable previously in-fabricable forms, and may even allow for use in harsh environments or extra-terrestrial domains.

## References and Notes


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**Supplementary Materials**




**Fig. S1.** System overview. (**1**)-(**4**) shows the sequence for the construction of a single segment of the composite tube with a single robot. (**1**) is the initial setup of the system, consisting of a spool of fiberglass thread, steel base, resin reservoir, and a single robot. The robot is tethered to the base via the black cable, which provides resin, electrical power, and communication with the resin pump. (**2**) shows an inflated robot, with UV LEDs turned on, as it winds a single segment. (**3**) shows a deflated (and hence delaminated) robot, after completing a third segment, it has driven up and tilted itself to curve the next segment of the composite tube. (**4**) Shows the robot inflated once more, with an overlap over the previous segment, and is ready to wind another segment.

**Fig. S2.** The final structure remains undamaged after several months in various weather conditions.

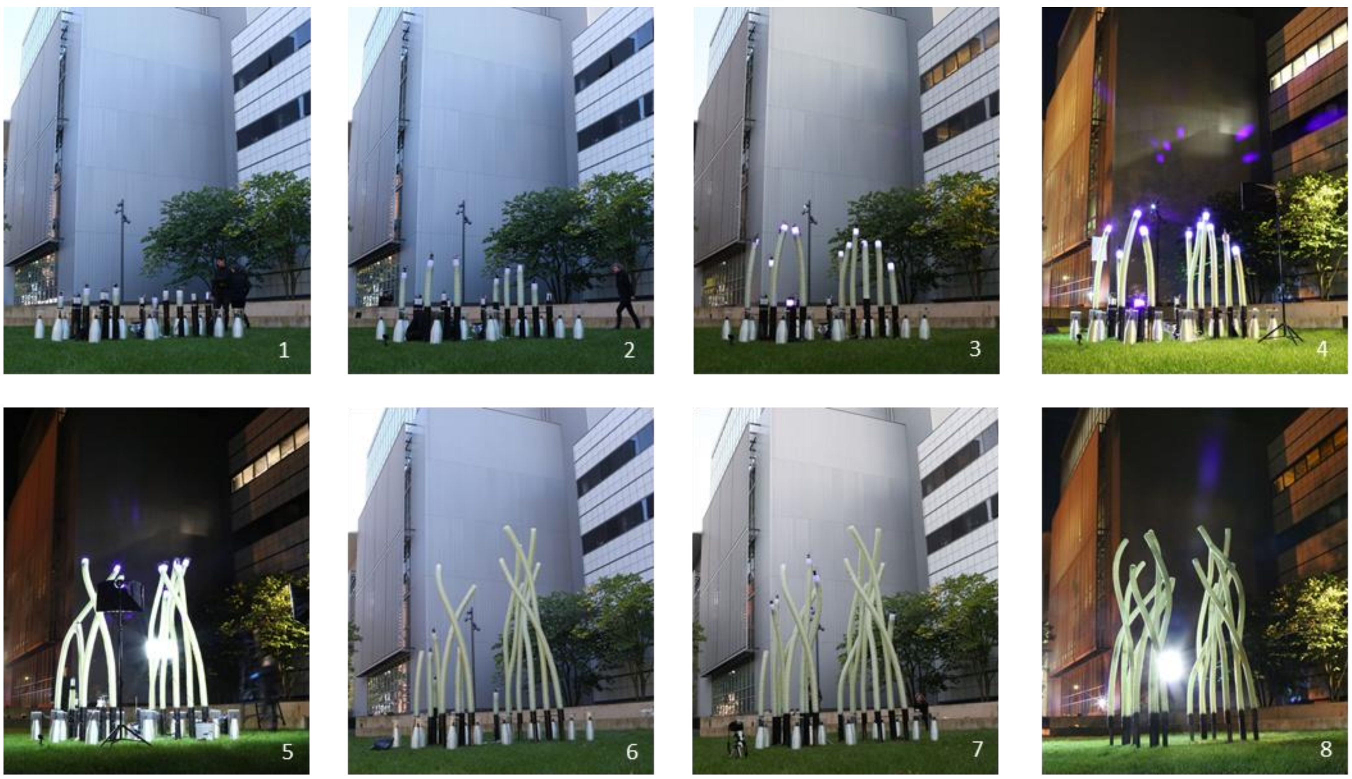


**Fig. S3.** Timelapse of the architectural-scale print over the course of two days.

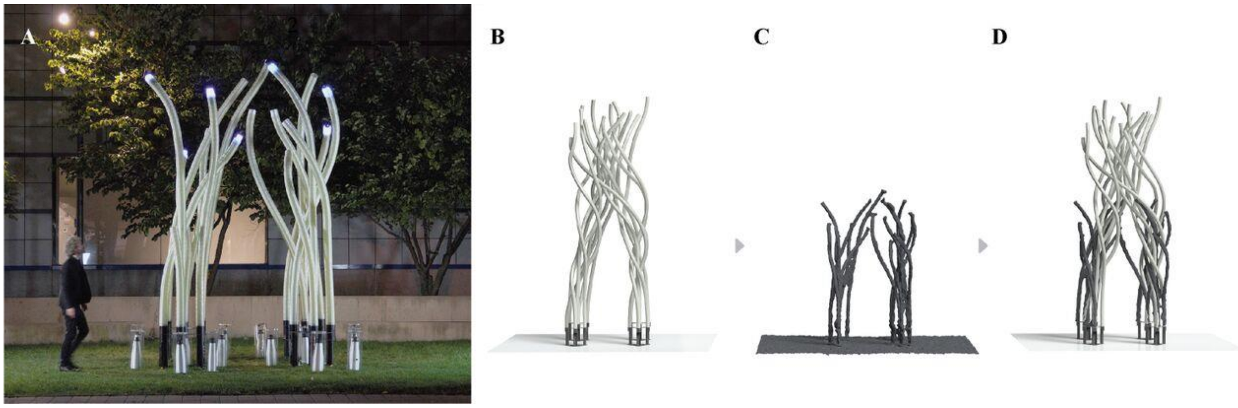


**Fig. S4.** (**A**)-(**D**) are all shown from the same perspective. (**A**) shows the actual completed structure, (**B**) is the initial design of the structure, (**C**) is a photogrammetry scan of the structure using Pix4D, and (**D**) is (**B**) and (**C**) overlaid on each other to illustrate the error and drift that occurs due to inaccuracies in the localization process.

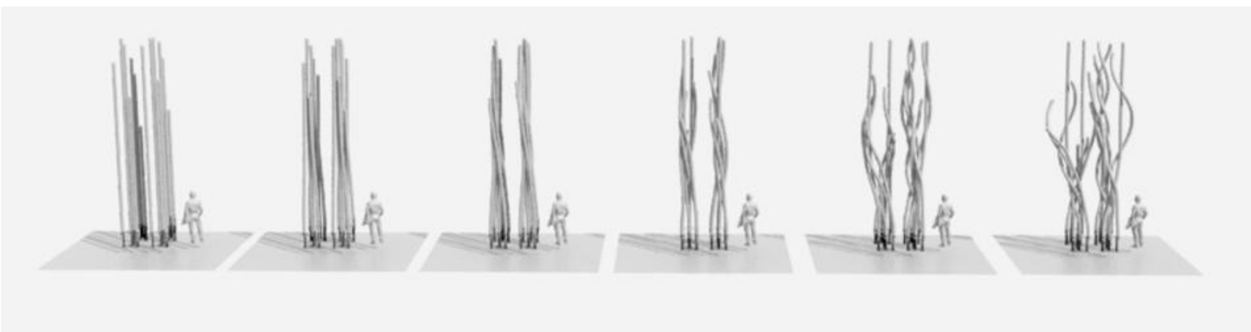

**Fig. S5.** From left to right, shows how changing curling bias affects the overall structure

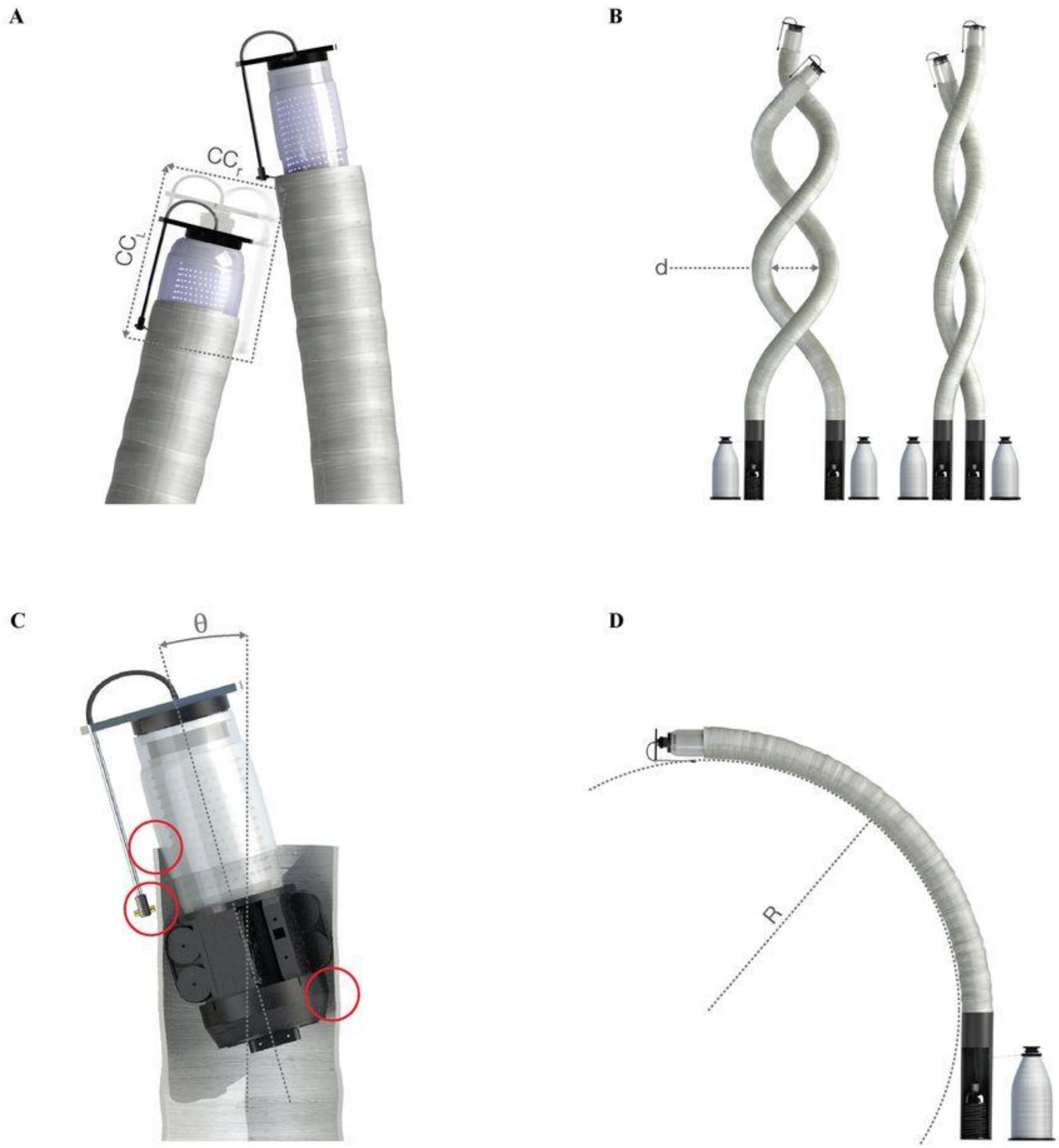


**Fig. S6.** Relation between robot geometry and overall fabrication constraints are shown here. In (**A**), the protruding sections of the robot, in addition to the winding motions of the arm, create a collision cylinder *CC*, with radial $CC_R$ and linear $CC_L$ components. This affects the minimum distance *d* that tubes can be fabricated together as shown in (**B**). Three points on the robot body can self-collide with its own tube, which limits the maximum angle $\Theta$ that the robot can tilt, shown in (**C**). In turn, this limits the minimum curve radius *R* of its own tube, highlighted in (**D**).

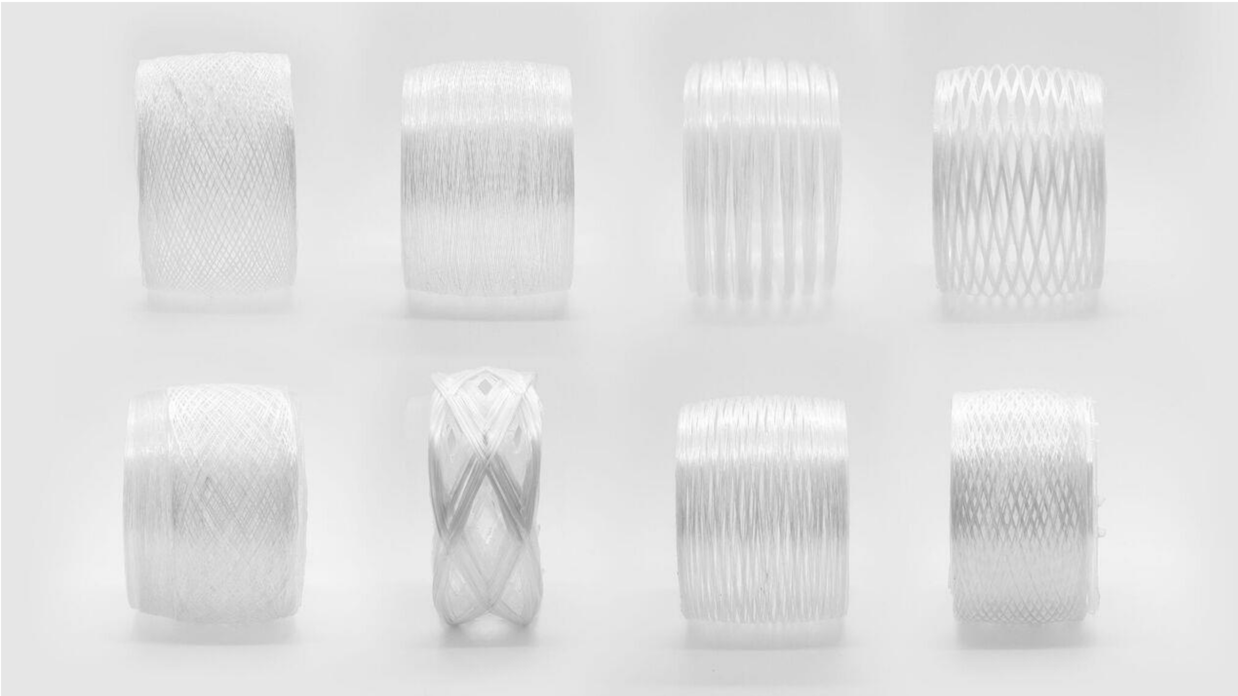

**Fig. S7.** Various fiber patterns wound using a single Fiberbot, achieved by varying speed ratios between the linear and rotary motions of the wind arm.

**Fig. S8.** Concept rendering of the case study before construction.

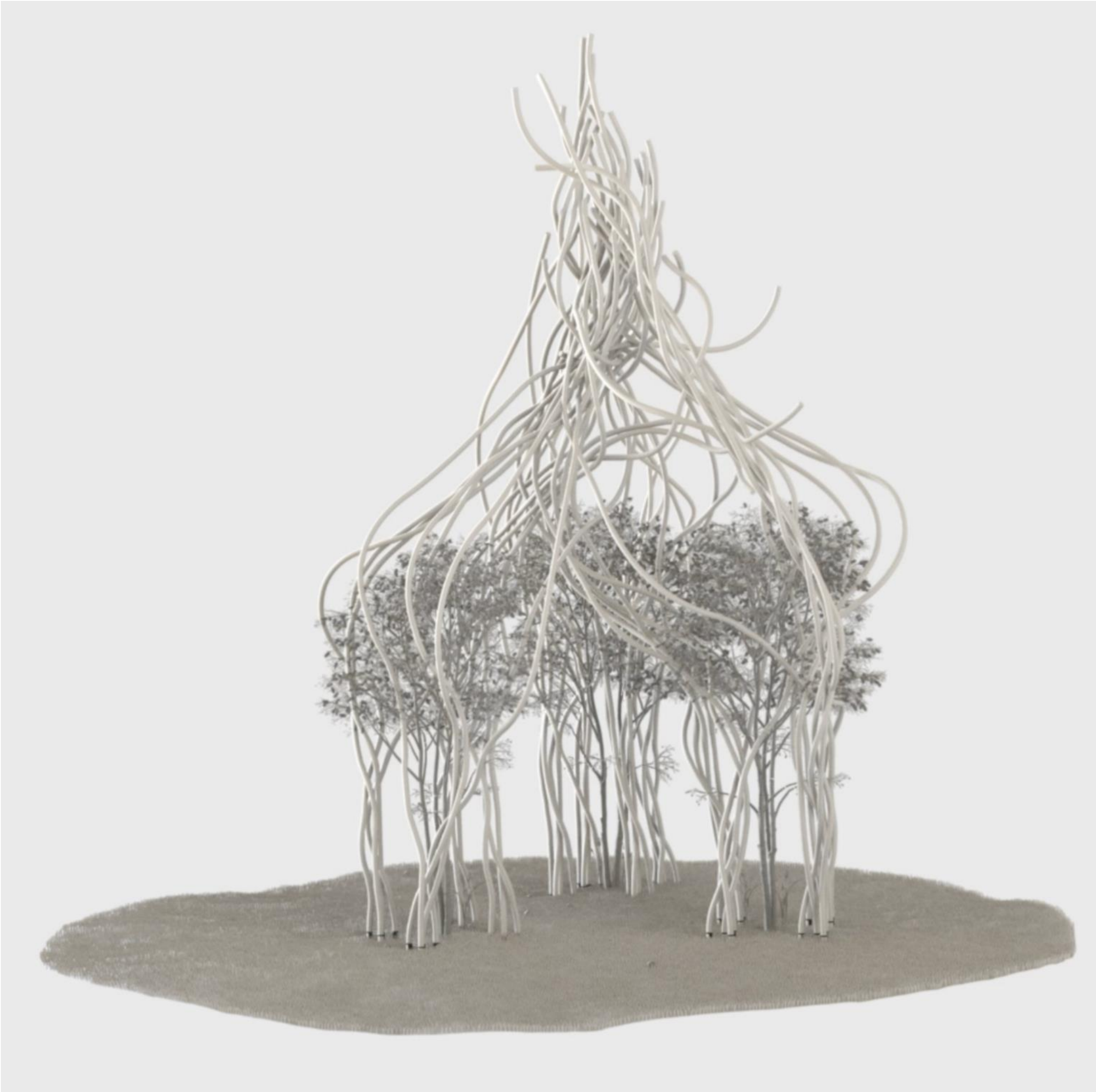

**Fig. S9.** Concept rendering where Fiberbots can detect and avoid arbitrary obstacles, the flocking based design method can still work at build-time.

**Fig. S10.** Photo of a single Fiberbot.